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From Optimization to Adaptation: Shifting Paradigms in Environmental Management and Their Application to Remedial Decisions

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ABSTRACT

Current uncertainties in our understanding of ecosystems require shifting from optimization-based management to an adaptive management paradigm. Risk managers routinely make suboptimal decisions because they are forced to predict environmental response to different management policies in the face of complex environmental challenges, changing environmental conditions, and even changing social priorities. Rather than force risk managers to make single suboptimal management choices, adaptive management explicitly acknowledges the uncertainties at the time of the decision, providing mechanisms to design and institute a set of more flexible alternatives that can be monitored to gain information and reduce the uncertainties associated with future management decisions. Although adaptive management concepts were introduced more than 20 y ago, their implementation has often been limited or piecemeal, especially in remedial decision making. We believe that viable tools exist for using adaptive management more fully. In this commentary, we propose that an adaptive management approach combined with multicriteria decision analysis techniques would result in a more efficient management decision-making process as well as more effective environmental management strategies. A preliminary framework combining the 2 concepts is proposed for future testing and discussion.

Keywords: Adaptive management   Risk assessment   Decision analysis   Environmental management   Remediation

Debate and Commentary

INTRODUCTION

Developing a management strategy to address an environmental problem presents risk managers with a number of complex, even daunting, challenges. Natural and human-made ecosystems can contain multitudes of species and a variety of landscapes. They may be simultaneously straining under the pressure of human development, and analyses of them can be highly uncertain. Amid all this uncertainty, the manager must balance competing forces to find a resource-efficient, technically supportable, and effective management strategy.

Traditional environmental management approaches (such as management of contaminated sites, natural resource management, etc.) often do not provide a clear and systematic decision rationale. The uncertainties that exist in field-collected data and modeling results, especially given the practical limitations of technical expertise, schedule, and finances, mean that some level of uncertainty is unavoidable when managers commit to selection of a management option. This uncertainty is difficult for managers to quantify and systematically incorporate into decisions. Modeling is often used to justify implementation of a management alternative, but modeling intercomparisons have revealed a large degree of uncertainty in model predictions even for simple ecosystems. For example, Linkov and Burmistrov (2003, 2005) report differences of up to 7 orders of magnitude among model estimations of radionuclide concentrations in a strawberry plant sprayed with contaminants under well-controlled conditions.

In the traditional decision-optimization process (Figure 1a), decision objectives are set and held static over time. Different management strategies are then considered as possible ways to attain the desired goals. Although risk analysis or modeling may influence the alternative selection process, other factors (political, social, or economic) can actually dominate the decision. Once the management alternative is subsequently implemented, its performance may or may not be monitored closely. It will likely be evaluated much later, such as at a 5-y Superfund review, at which point a different alternative may be favored instead. If the initial selection process was contentious, there may be a reluctance to revisit the decision process. Additionally, any changes may be perceived as a failure of the initial strategy.

Adaptive management, by contrast, provides a systematic tool for the dynamic linkage of environmental management with new information on ecosystem performance or social and economic priorities (Figures 1b and c). In an adaptive management paradigm, the uncertainty in understanding the environment is acknowledged at the outset, and strategies are formulated to manage or reduce it. The basic adaptive management process is straightforward: decision makers choose a management action, monitor the effects of the action, and adjust the action based on the monitoring results

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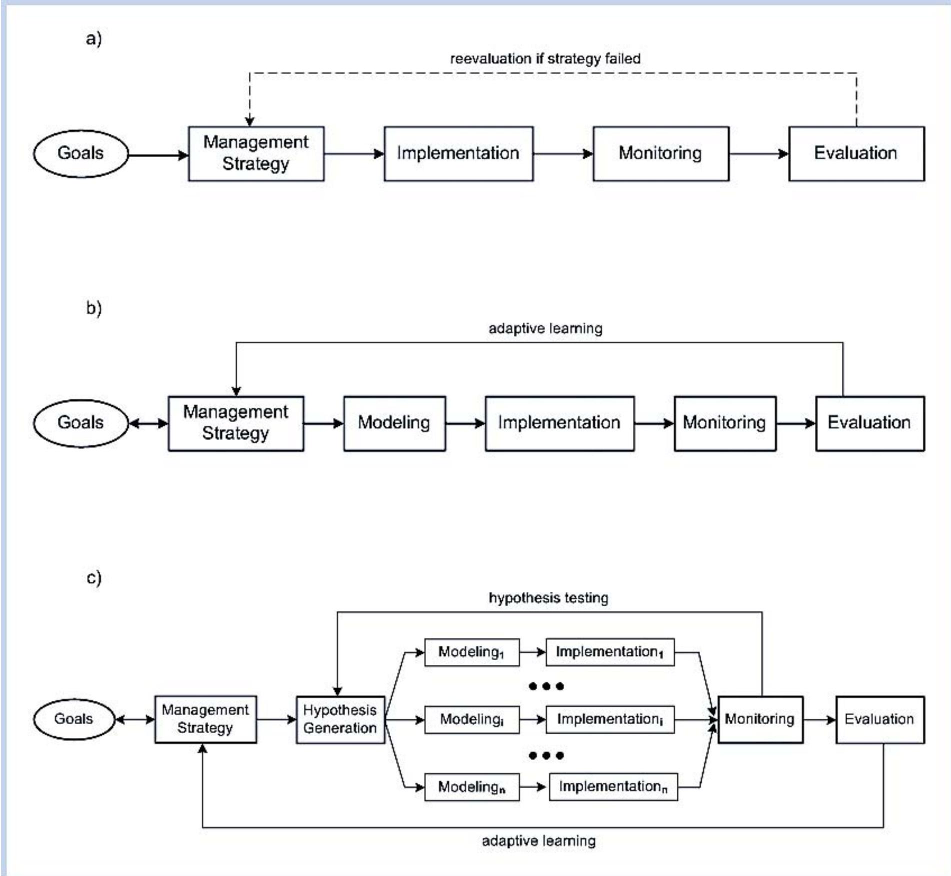

Figure 1. (**a**) Traditional management; (**b**) passive adaptive management; and (**c**) active adaptive management.

and updated social and economic factors. Literature reviews have highlighted 2 types of adaptive management, passive (Figure 1b) and active (Figure 1c; Wilhere 2002). Passive adaptive management involves implementing 1 management strategy at a time, whereas the active adaptive management process implements multiple management alternatives simultaneously and continuously examines them to assess their relative performance. In both cases, environmental modeling is a crucial component of the process that allows integration of monitoring data into an estimate of effectiveness. During the adaptive management process, in contrast to traditional management, changes are expected and discussed, learning is emphasized, and even objectives can be revised based on the performance of a management alternative, changing societal values, or institutional learning.

Yet despite the promise of adaptive management, current environmental management practice has not widely accepted or used adaptive approaches. Although adaptive management has been recommended by many state and federal government agencies, applications vary in their implementation of the concept, and there is no framework that robustly incorporates adaptive management in environmental practice. This commentary summarizes our detailed literature review (Satterstrom et al. 2005) and proposes the combination of an adaptive management philosophy with decision analysis tools (Linkov et al. 2004; Kiker et al. 2005; Linkov et al. 2005) to offer a structured framework for selecting the best management strategy. This proposed framework could provide an approach for guiding environmental policy decisions in the face of uncertainty and would result in a systematic approach for allocating resources to address environmental problems and needs.

ADAPTIVE MANAGEMENT: METHODS AND APPLICATIONS

The recent publication *Adaptive Management for Water Resources Project Planning* (NRC 2004) provides a comprehensive description of adaptive management processes. In our review (Satterstrom et al. 2005), we use the 6 elements of adaptive management described by the National Research Council (NRC) to summarize multiple studies in which elements of adaptive management were applied. This section introduces these elements and presents several important studies that help with understanding the draft framework we propose later in this article. Readers are encouraged to consult our full review for more details.

Management objectives that are regularly revisited and accordingly revised

The 1st key element of adaptive management is a regular review of a project's objectives. Stakeholders must agree on what the basic objectives are, and the project's objectives should be reviewed when new information becomes available. Interestingly, few adaptive management articles explicitly discuss the updating and revision of objectives as new information is acquired. Many, in fact, take it for granted that their objectives are static goals. The NRC explicitly incorporates this step in its framework for the remediation of contaminated Navy sites (NRC 2003).

A model of the systems being managed

Modeling tools are integral to many adaptive management processes. They provide a basis for understanding why change occurs in the environment and can also be used to predict the effects of possible management strategies during the selection process. Quantitative mathematical models are preferred, including probabilistic analyses. For example, Conroy et al. (2005) use Markov Chain Monte Carlo (MCMC) modeling to predict harvest rates for American black ducks. However, because adaptive managers often face substantial uncertainty, conceptual models can be used in addition, or in place of, more quantitative descriptions of the environmental setting and problem. Our review indicates that modeling is probably the most widely used adaptive management component, although models often address ecological processes only. Integrated models that explicitly incorporate decision alternatives as well as costs and social considerations are still rare.

A range of management choices

An active adaptive management process includes the generation of a range of management choices. Implementing multiple alternatives simultaneously, along with a control, can provide information similar to that of a scientific experiment. Our review reveals that examples of passive adaptive management dominate the literature. Nevertheless, there are a few good examples of the active method. Allison et al. (2004) model and evaluate multiple options as they come to a conclusion about deactivation of different tracts of logging roads to manage landslide risk and ecological health. Walters and Hilborn (1978), in an important early paper, discuss adaptive management in the context of the optimization of harvesting policies for exploited populations.

Monitoring and evaluating outcomes

The adaptive management process requires monitoring and evaluation of outcomes to determine which option performs the best. This is, by far, the most heavily emphasized aspect of adaptive management. Many monitoring frameworks have been developed, ranging from simple data collections to sophisticated statistical methods (Sit and Taylor 1998).

Mechanisms for incorporating learning into future decisions

Because the central idea of adaptive management is to reduce uncertainty about the system being managed, learning is an important goal for any project. McDaniels and Gregory (2004), for example, recommend that learning be a fundamental objective of the management decision process. Kiker et al. (2001) emphasize that current knowledge may be insufficient for effective Everglades restoration, and they advance adaptive management as a way to promote holistic understanding useful to decision makers and political representatives.

A collaborative structure for stakeholder participation and learning

Management should be undertaken with a collaborative structure for stakeholder participation and learning. All affected parties need to be represented in the process and need to gain information through the process. Many case studies have shown that stakeholder involvement is essential to adaptive management (e.g., Johnson 1999; Pinkerton 1999). When management fails to incorporate stakeholders—especially the general public—into decisions, distrust and political tension result.

EMERGENCE OF ADAPTIVE MANAGEMENT IN REGULATORY AGENCIES

Regulatory agencies in the United States and around the world recommend adaptive management, and this section provides a brief summary of those efforts. One interesting feature of our review is that agencies often implement or emphasize only specific elements of the adaptive management process and not its holistic framework. The US Environmental Protection Agency (USEPA), for instance, has implemented adaptive management in many projects. Among the most notable are the Mississippi River Basin project, which uses models and monitoring quite heavily in attempts to reduce the uncertainties surrounding the biochemical mechanisms of hypoxia (USEPA 1999; USEPA 2001), and the Lake Superior Lakewide Management Plan (USEPA 2002), which calls for a less structured, periodic refining of management strategies based on new information and public input. These examples demonstrate the variation that can exist among adaptive management projects: whereas the Mississippi River Basin project emphasizes the modeling and monitoring aspects of adaptive management but focuses less on stakeholder involvement, the Lake Superior project does the opposite, soliciting public input and placing less emphasis on modeling or monitoring.

The Department of Defense has been exploring adaptive management concepts. An NRC book (NRC 2003) provides a thorough overview of how to apply adaptive management to the remediation of contaminated sites, tailored to the cleanup of Navy facilities. This framework emphasizes experimentation, monitoring and evaluation, and public involvement. Adaptive site management, implemented according to the NRC, shares many of the elements that we suggest are key to successful adaptive management. The US Army Corps of Engineers uses adaptive management principles in its water resources projects. These efforts vary from large-scale restoration (Florida Everglades; USACE and SFWMD 2001) to large-scale navigation (Upper Mississippi River; NRC 2004) to river basin studies (Richter et al. 2003).

The National Oceanic and Atmospheric Administration (NOAA) uses adaptive management, especially in its coastal management and coastal habitat restoration activities (NOAA 2004c). The adaptive management process implemented in these cases is passive, involving iterations of a 5-step cycle: plan, act, monitor, evaluate, and adjust (NOAA 2004a). NOAA emphasizes the monitoring and evaluation elements of adaptive management. Sutinen et al. (2000) developed a monitoring and assessment framework for the agency, but the degree to which its projects include other aspects, such as modeling or revisitation of objectives, can be limited. NOAA has used adaptive management in projects such as shore restoration in the Pacific Northwest, USA, the restoration of native plant species in a Rhode Island, USA, marsh, and in larger projects such as the Louisiana, USA, coastal wetlands, where there is again an emphasis on learning through monitoring (NOAA 2004b).

Adaptive management is also being implemented within many US agencies and departments. Although the Department of Energy's (DOE) National Environmental Policy Act

(NEPA) Task Force report "Modernizing NEPA Implementation" (DOE 2003) finds that the department could employ adaptive management to a much greater extent, the DOE already uses it in managing the environmental effects of hydroelectricity production. One example is the adaptive management plan for balancing salmon conservation with electricity production in the Columbia River basin of Washington state, (DOE 2002), which emphasizes the use and continual refinement of advanced mathematical models. More generally, the Federal Energy Regulatory Commission (FERC) may choose to expedite license issuance for power plant construction under the condition that adaptive management be used at the site (FERC 2000).

Varying elements of adaptive management have been implemented in Canada as well. Fisheries and Oceans Canada has advanced a socioeconomic framework for ecosystem-based fisheries management (Rudd 2004), and Environment Canada has recommended adaptive management in general to compensate for humans' lack of complete understanding of complex ecosystems (Environment Canada 2004). It is on the provincial level, however, where we see the greatest use of adaptive management. British Columbia has thorough guides to adaptive management published locally (Taylor et al. 1997; Nyberg 1999), and the British Columbia Forest Service is currently implementing many pilot adaptive management projects, including adaptive management of livestock grazing, river and stream banks, forest recreation sites, and grizzly bear habitat, among others (BCFS 2000).

Many international agencies and organizations also call for the use of adaptive management in environmental policy. In the European Union, the Commission of the European Communities and the World Wildlife Federation both recognize adaptive management as a potential solution for managing over-harvested fisheries stocks (CEC 2001; WWF 2001a). The Biodiversity Support Program has published a general guide to adaptive management that explicitly relates adaptive management to the scientific method and emphasizes learning and reducing uncertainty (WWF 2001b). Additionally, the RAND Corporation (Lempert et al. 2003) recommends adaptive management and computer modeling as a way to help conduct long-term policy analysis, albeit in a general fashion.

INTEGRATING ADAPTIVE MANAGEMENT WITH MULTICRITERIA DECISION ANALYSIS

Faced with significant uncertainty when predicting ecosystem dynamics, natural resource managers are moving away from traditional management toward more adaptive approaches. Unlike traditional management schemes designed to find, implement, and defend a single optimal remedial strategy, the adaptive management paradigm explicitly acknowledges the existence of uncertainty and the limitations in our ability to predict system change in response to physical, biological, and social pressures. Our review indicates that the concept of adaptive management is well respected in academia, and many government agencies have recommended its application.

Despite recommendation for its use, adaptive management has only been implemented on a limited basis (e.g., on large-scale natural resource management projects such as the Everglades and Grand Canyon National Park). Moreover, the quantitative tools and methods for implementing adaptive management strategies are not systematized, and no framework is available for integrating and organizing the people, processes, and tools required to make structured and defensible environmental management decisions. We believe that multicriteria decision analysis (MCDA) is a solution for integrating heterogeneous information (technical, social, and political), as well as for explicitly incorporating decision makers' and stakeholders' value judgments (Linkov et al. 2004; Kiker et al. 2005).

MCDA is a structured decision-making process (Figueira et al. 2005) that begins with a collection of decision makers, scientists, and other stakeholders who define a problem and propose alternatives to solve that problem. The group then decides what criteria it will use to judge the alternatives against one another. The alternatives are judged on each criterion, the relative importance of each criterion is determined, and the scores are compared to identify the best alternative. The advantages of using MCDA techniques over other less-structured decision-making methods are numerous: MCDA provides a clear and transparent way of making decisions and also provides a formal method for combining information from disparate sources. These qualities make decisions made through MCDA more defensible than decisions made through less-structured approaches. We believe that a combination of adaptive management and MCDA will provide a powerful framework for a wide range of environmental management problems. It will allow both structured, clear decisions to be made and also the adjustment of those decisions based on their performance.

A general decision framework proposed in Linkov et al. (2004) can be modified to include the adaptive management process (Figure 2). The degree of activity and involvement of 3 general sets of people (decision makers, scientists and engineers, and stakeholders) is symbolized in Figure 2 by dark lines for direct involvement and dotted lines for less-direct involvement. Although the actual membership and the function of these 3 groups can overlap or vary, the roles of each are essential in maximizing the utility of human input. Each group has its own way of viewing the world, its own method of envisioning solutions, and its own societal responsibility. Policy- and decision makers spend most of their effort defining the problem's context and the overall constraints on the decision. In addition, they may have responsibility for the final decision and policy implementation. Stakeholders may provide input to define the problem, but they also contribute by formulating performance criteria and contributing value judgments for weighting the various success criteria. Depending on the problem and regulatory context, stakeholders may also have some responsibility in ranking and selecting the best option. Scientists and engineers may act as stakeholders, but generally they have the most focused role in that they provide the measurements or estimations of success for the various alternatives on the desired criteria.

The decision-making process itself is in the center of the figure. Although it is reasonable to expect that the process may vary in specific details among regulatory programs and project types, emphasis should be given to designing an adaptive management structure that suits local concerns while still producing the required outputs. The process depicted in Figure 2 follows 2 basic activities: (1) generating management alternatives, success criteria, and value judgments; and (2) ranking the alternatives by applying value weights. The 1st part of the process generates and defines

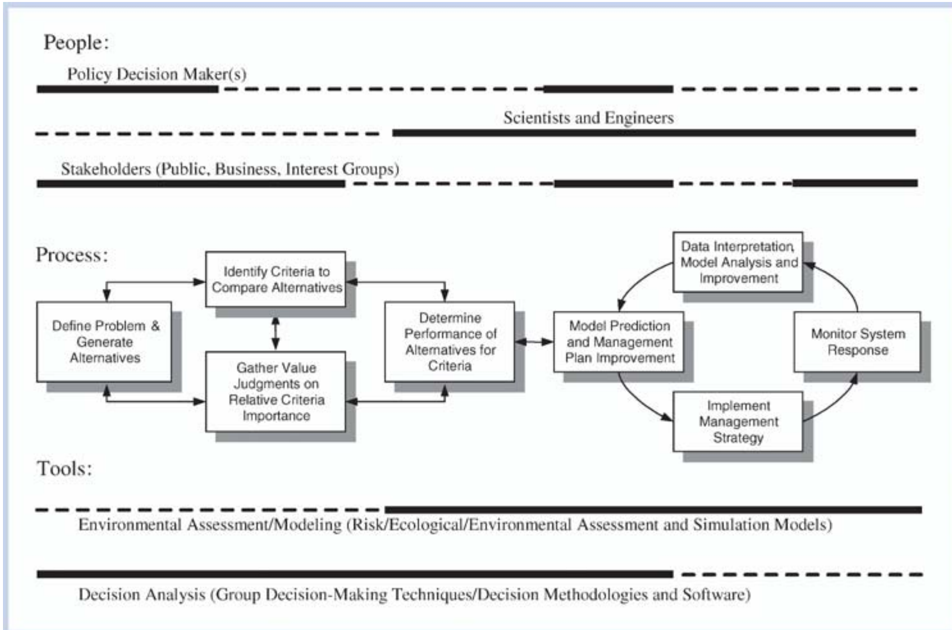

Figure 2. Adaptive decision framework. Solid lines represent direct involvement for people or use of tools; dashed lines represent less-direct involvement or use.

choices, performance levels, and preferences. The 2nd part methodically prunes nonfeasible alternatives by 1st applying screens (for example, overall cost, technical feasibility, or general societal acceptance) followed by a more detailed ranking of the remaining options by decision-analysis techniques that use the various criteria levels generated by environmental tools, monitoring, or stakeholder surveys.

As shown in Figure 2, the tools used within group decision-making and scientific research are essential elements of the overall decision process. The applicability of the tools is symbolized by solid lines (direct or high utility) and dotted lines (indirect or lower utility). Decision-analysis tools help to generate and map stakeholder preferences as well as individual value judgments into organized structures that can be linked with risk analysis, modeling and monitoring, and cost estimates. Decision-analysis software can also provide useful graphical techniques and visualization methods to express the gathered information in understandable formats. When changes occur in the requirements or the decision process, decision-analysis tools can respond efficiently to reprocess and iterate with the new inputs. The framework also provides a focused role for the detailed scientific and engineering efforts invested in experimentation, environmental monitoring, and modeling, allowing each to play a unique and valuable role in the decision process without attempting to apply either type of tool beyond its intended scope.

The proposed framework is iterative and adaptive at each phase and can be cycled through many times in the course of complex decision making. This framework can be built on current optimization-style models, but it applies them in an iterative manner wherein management plans are reexamined on a continual basis rather than only when they fail. The continual adaptive cycle of prediction, implementation, monitoring, and evaluation allows new information to be incorporated into the decision-making process, and the decision-analysis tools both give structure to the process and ensure that no important information is overlooked. Even a 1st-pass effort can efficiently point out challenges that may occur, key stakeholders to be included, or modeling studies that should be initiated.

DISCUSSION AND CONCLUSION

We are not the 1st to propose an integration of decision-analysis methods with adaptive management (see Pastorok et al. 1997; Rauscher et al. 2000; Peters and Marmorek 2001), but the comprehensive and integrated framework that we propose offers a number of benefits to contaminated site remediation projects. We believe that this framework will be useful in practice, which is exemplified by the difference between the ad hoc management decision paradigm currently implemented at contaminant remediation sites and the same process conducted under an adaptive management paradigm (Figure 3). Most projects use very front- and end-loaded processes, with little structure for making the actual decisions. Thus, even when managers spend large amounts of time attempting to determine an optimal management strategy, they are still constrained to a vague framework. Using adaptive management and multicriteria decision analysis, however, gives structure to the decision-making process and allows the manager to learn about the system being managed and modify the management strategy based on new knowledge. Such a framework could be of great assistance to managers, saving them both time and resources, because it helps them to understand the trade-offs involved between different management alternatives; enables them to make justified, informed choices about remedial options; and allows them to adjust these options, as necessary, through time.

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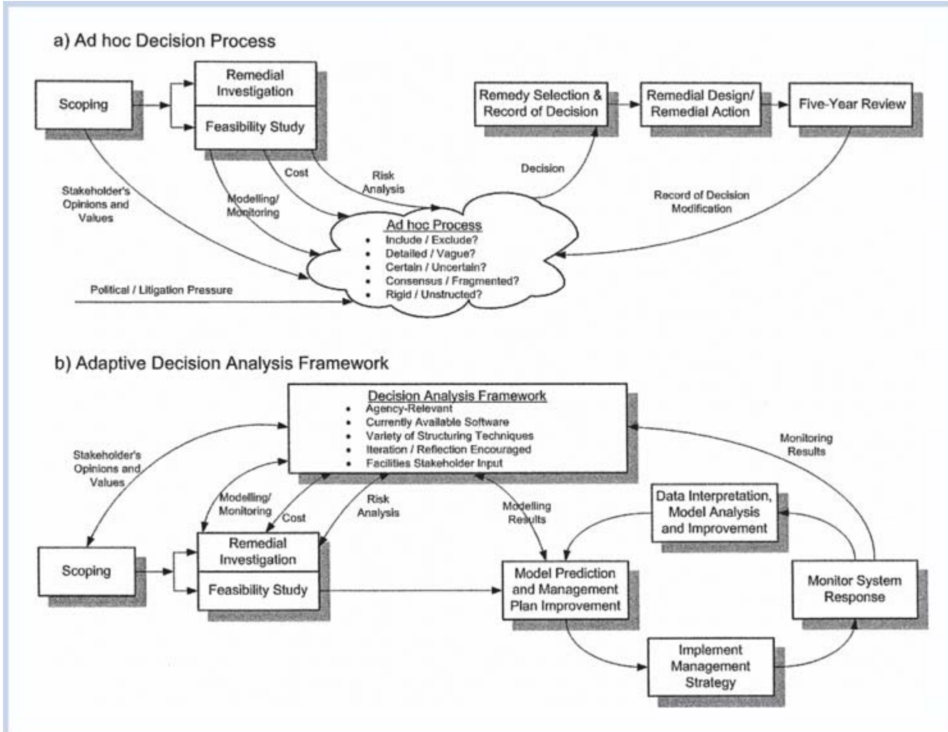

Figure 3. A comparison of environmental management strategy selection between (**a**) command-and-control management, and (**b**) adaptive management with decision analysis.

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